larity. (It corresponds to the setup in Ref. 5 to initiate island formation in a reversed pinch.) However, the model and its subsequent physics are general enough to pertain to many other cases, since nonlinear developments are common over many situations, e.g., the external driven pinch reconnection, the development of the internal coalescence instability, etc.

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[1]H. Alfvén, L. Lindberg, and P. Mitlid, J. Nucl. Energy, Part C 1, 116 (1960).

[2]J. H. Irby, J. F. Drake, and H. R. Griem, Phys. Rev. Lett. 42, 228 (1979).

[3]T. R. Jarboe, I. Henins, H. W. Hoida, R. K. Linford, J. Marshall, D. A. Platts, and A. R. Sherwood, Phys. Rev. Lett. 45, 1264 (1980).

[4]W. C. Turner *et al.*, Lawrence Livermore Laboratory Report No. UCRL-85122, 1980 (unpublished).

[5]F. Brunel and T. Tajima, Bull. Am. Phys. Soc. 25, 884 (1980).

[6]E. J. Caramana and D. D. Schnack, in Proceedings of the 1981 Sherwood Theory Meeting (unpublished), Paper No. 3B38.

[7]B. B. Kadomtsev, Fiz. Plazmy 1, 710 (1975) [Sov. J. Plasma Phys. 1, 389 (1975)].

[8]W. Park, Bull. Am. Phys. Soc. 26, 845 (1981).

[9]F. Brunel, J. N. Leboeuf, T. Tajima, J. M. Dawson, M. Makino, and T. Kamimura, J. Comput. Phys. 43, 268 (1981).

[10]F. Brunel, T. Tajima, J. N. Leboeuf, and J. M. Dawson, Phys. Rev. Lett. 44, 1494 (1980).

[11]S. I. Syrovatskii, Zh. Eksp. Teor. Fiz. 60, 1727 (1971) [Sov. Phys. JETP 33, 933 (1971)].

[12]E. N. Parker, Astrophys. J. Suppl. Ser. 77, 177 (1963).

[13]H. E. Petschek, in *Symposium on the Physics of Solar Flares*, edited by W. N. Hess (NASA, Washington, D.C., 1964), p. 425.

[14]T. Sato and T. Hayashi, Phys. Fluids 22, 1189 (1979).

[15]D. Biskamp and H. Welter, Phys. Rev. Lett. 44, 1069 (1980).

Ion Heating with High-Power Perpendicular Neutral-Beam Injection in the Poloidal Divertor Experiment (PDX)

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Plasma heating by near-perpendicular injection of up to 7.2 MW of neutral-beam power has been studied in the PDX tokamak. Collisionless plasmas with central ion temperatures up to 6 keV have been obtained. The total plasma energy, which is dominated by contributions from beam and thermal ions, rises linearly with increasing beam power. The ion heating efficiency in PDX is comparable to that measured in the Princeton Large Torus with tangential injection.

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Neutral beams have been used for auxiliary heating in many tokamak experiments. In most, the beams have been injected essentially tangentially to the toroidal magnetic field. For future large machines, perpendicular injection is attractive for achieving good beam penetration at beam energies that are practical for positive ion sources. Up to ~1 MW was injected near-perpendicularly into the TFR tokamak.[1] On the Poloidal Divertor Experiment (PDX), these results have been extended to power levels of 7.2 MW to examine the effectiveness of perpendicular injection in heating plasmas to the high-temperature, low-collisionality regime which will be typical of the next generation of devices.

The PDX tokamak is described by Meade *et al.*[2]

Neutral-beam injection experiments have been conducted in both circular cross-section limiter discharges with water-cooled carbon limiters and in inside-dee diverted discharges, in which titanium neutralizer plates absorb the incident power. In both configurations, titanium gettering in the upper and/or lower domes is used.

The PDX beam injection system developed by the joint Plasma Physics Laboratory–Oak Ridge National Laboratory Heating Project consists of four beam lines each with a 50-keV ion source.[3] The beams are oriented to inject along the direction of the plasma current at a tangency radius of 35 cm, giving an angle of 14° from the perpendicular at the center of the vessel. The maximum power injected into the vessel is 7.2 MW with deuterium beams and 5.5 MW with hydrogen. The beam duration is typically 150 ms, which is long enough to obtain thermal equilibrium.

The central ion temperature is deduced from measurements of the Doppler broadening of Ti-XXI $K\alpha$ line at 2.61 Å with a crystal spectrometer and from measurements of the charge-exchange neutral spectrum. During high-power injection into plasmas of line-average density, $\bar{n}_e$, less than 4×10^{13} cm^{-3}, these measurement techniques agree within 10%.

Figure 1 shows the central ion temperature as a function of $P_{\rm abs}/\bar{n}_e$ for limiter discharges with $\bar{n}_e$ in the range of $(2-4)\times10^{13}$ cm^{-3}. $P_{\rm abs}$ is the injected power less the power calculated to shine through the plasma. In high-current (500 kA)

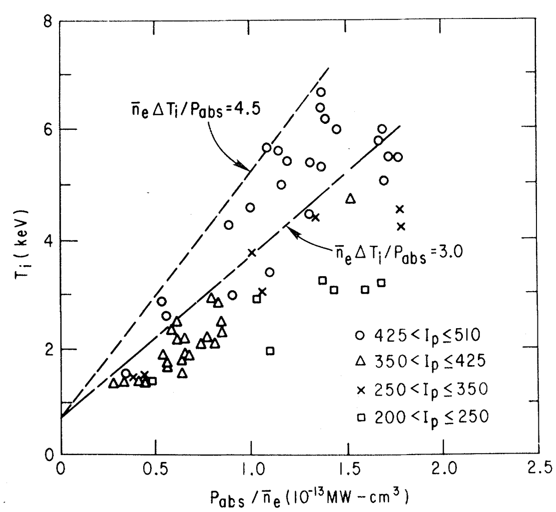

FIG. 1. The central ion temperature in circular hydrogen discharges ($B_T > 1.97$ T) increases with $P_{\rm abs}/\bar{n}_e$ during deuterium injection as determined by charge-exchange measurements.

and high-field (2.2 T) discharges, ion temperatures of up to 6 keV were obtained. In these high-temperature plasmas, the ion collisionality, ν_i^*, reached a minimum of $\sim2\times10^{-2}$, with $\nu_i^* < 0.1$ over more than half of the minor radius.

The ion heating quality factor, defined as $\eta_i \equiv \bar{n}_e \Delta T_i/P_{\rm abs}$, is a useful parameter to describe ion heating and in particular to make comparisons with the results from PLT (Princeton Large Torus) experiments. We have found using our transport analysis code[4,5] that η_i depends upon ion thermal transport (conduction plus convection), but is relatively insensitive to other variables. The transport calculations include electron-ion coupling, a convective loss term $[\frac{5}{2}\nabla\times(n_i T_i v_r)]$, and neoclassical thermal conductivity,[6] $\kappa_i^{\rm NC}$, enhanced by an adjustable factor. Either multiplying or dividing a typical $n_e(r)$ by 1.5 with $T_e(r)$ fixed, we find that η_i calculated in the code remains nearly constant. When we fix $\bar{n}_e$ but vary the shape of the density profile from the square root of a parabola to a parabola squared, we find that η_i is again constant because the improved penetration with peaked profiles is compensated by the increased particle density of the central region. Varying $T_e(r)$ across the profile by 15% we find $\Delta T_i(0) \simeq \Delta T_e(0)$; hence, for $T_i(0) \gg T_e(0)$, η_i is relatively insensitive to T_e. Varying the assumed $Z_{\rm eff}$ in the plasma composition from 1.5 to 3 has little effect on the calculated η_i. Finally, varying the beam tangency radius from 35 cm (PDX) to 124 cm (PLT) at $\bar{n}_e = 3\times10^{13}$ cm^{-3} does not change η_i despite small differences in the beam deposition profile. However, in high-current discharges that were studied, η_i was found to be approximately inversely proportional to ion thermal losses from the core ($r \leq a/2$).

From Fig. 1, it is seen that the ion heating quality factor has reached values up to 4.5×10^{13} cm^{-3} keV MW^{-1} in the PDX high-current discharges, although η_i is somewhat variable. In discharges with lower currents, η_i is smaller. In divertor and limiter discharges at the same current $I_p = 400$ kA, the values of η_i are comparable. In PLT, with tangential injection, η_i was typically 4.5 in discharges with ion temperatures[4,7] of 3–7 keV; however, during some periods the ion heating was poorer and η_i was about 3. The reasons for the variability in ion heating in both devices are not known, but it is nonetheless clear that the ion heating in PDX with perpendicular injection is comparable to that in PLT with tangential injection, for similar plasma current, toroidal field, and minor and major radii.

For high-current (500 kA) and high-field (2.2 T) discharges, the ion transport modeling using the measured electron temperature and density profiles correctly predicts the central ion temperature in PDX with $\kappa_i \sim (1-3)\kappa_i^{\rm NC}$. The ion temperature in PLT is correctly predicted from a similar ion thermal transport model.[4] At low densities, the ion power balance is dominated by convection and charge exchange, while at higher densities (typical of PDX operation) ion-electron coupling dominates the ion power balance. In neither case is pure neoclassical ion heat conduction a substantial part of the ion energy balance. In lower-current, lower-field discharges in PDX an enhancement of the neoclassical ion thermal conductivity by up to a factor of 5 was required to simulate the (reduced) central ion temperature.

The electron density and temperature profiles used in the analysis of the ion heating are measured with a 56-point, single-shot, horizontal Thomson scattering system. A summary of electron heating results is shown in Fig. 2. For $P_{\rm abs} < 2$ MW, in both circular and diverted discharges, the electron temperature rise on axis is about 0.5 eV/kW which is comparable with the heating rate on PLT. The line-average electron density in the diverted discharges was $\sim 3.3\times10^{13}$ cm^{-3} and in the circular discharges varied from 1.7 $\times 10^{13}$ cm^{-3} at the lowest to 3.9×10^{13} cm^{-3} at the highest beam power. At higher powers, the total stored energy continues to increase as a result of the density increase accompanying neutral beam injection in limiter discharges, although the heating rate $(\Delta T_e/P_{\rm abs})$ is reduced. Radiation losses are not significant in the electron power balance in the core of these discharges. Bolometric measurements indicate that the losses from the core by radiation and charge exchange are small (~10% of the input power), and measurements of the soft x-ray and ultraviolet spectra substantiate this conclusion.

In beam-heated limiter discharges ($D^0 \to H^+$, 500 kA, and $B_T = 2.2$ T) the global energy confinement time (at $r = a$) for the thermal plasma was about 23 ms, essentially independent of beam power. This is somewhat less than the best confinement time in similar ($D^0 \to H^+$) discharges on PLT in which τ_E was 27 to 30 ms.

Magnetic measurements[8] of $l_i/2 + \beta_\theta$ were used to investigate the scaling of the total plasma stored energy with power. Typically, the calculated change in the internal inductance, $l_i/2$, based on the measured electron temperature profiles, is small compared with the change in β_θ; thus the linear increase of $\Delta(l_i/2 + \beta_\theta)$ with beam power shown in Fig. 3 reflects mainly variations in β_θ. In 200-kA discharges, magnetic equilibrium analysis indicates that β_θ has reached 1.7, corresponding to $\beta_\theta \sim 0.5R/a$ at $q(a) = aB_T/RB_\theta = 7.5$. In 500-kA discharges at 2.2 T and $q(a) = 3$, the total plasma pressure corresponds to $\beta(0) \simeq 4.4\%$ and $\langle\beta\rangle \simeq 0.7\%$. No indication of saturation of β_θ with power such as that seen in ISX[9] and DITE[10] has been observed. In the PDX experiments, the major contribution to β_θ comes from the beam and thermal ions. Since the elec-

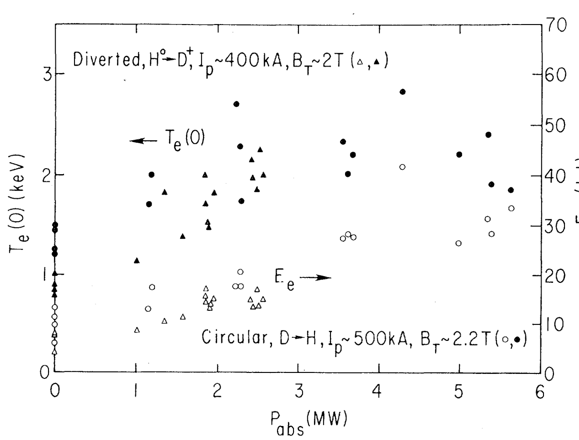

FIG. 2. Thomson scattering measurements of central electron temperature (closed circles and triangles) and stored electron energy (open circles and triangles) in both circular and diverted discharges.

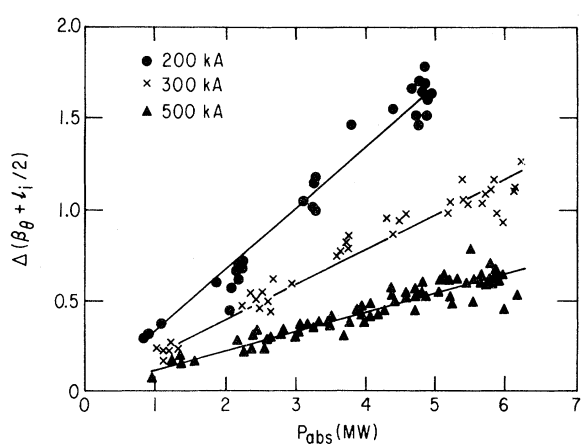

FIG. 3. $l_i/2 + \beta_\theta$ as determined by magnetic measurements in circular discharges ($B_T = 2.2$ T) increases linearly with absorbed power.

tron energy increases with beam power, the magnetic measurements imply that the stored energy in the beam and thermal ions also increases linearly with beam power.

The linear increase in beam stored energy with power is supported by charge-exchange measurements of the beam ion slowing-down distribution. The measured charge-exchange efflux as a function of both angle and energy shows good agreement with a bounce-averaged Fokker-Planck calculation for 500-kA plasmas. The magnitude of the beam-particle charge-exchange flux is found to be approximately proportional to the injected beam power. At lower currents, the agreement with the bounce-averaged calculation is poorer (presumably because of finite banana width effects which are not included) but the linearity of the charge-exchange flux with injected beam power is still observed.

In order to determine if the variation of $\Delta(l_i/2+\beta_\theta)$ with power shown in Fig. 3 could be due to accompanying variations in electron density, the electron density was varied in divertor discharges during beam injection from $\bar{n}_e=(2.5 \text{ to } 6.0)\times 10^{13}$ cm^{-3} by gas puffing. Under these conditions, $\Delta(l_i/2+\beta_\theta)/P_{\rm abs}$ did not change substantially. Thus, the variation of $\Delta(l_i/2+\beta_\theta)$ with power and plasma current is not significantly affected by associated changes in density.

In summary, ion temperatures of ~6 keV at electron densities of $(3-4)\times 10^{13}$ cm^{-3} have been obtained in PDX with perpendicular injection. Ion heating improves with current, and at 500 kA the heating is equivalent to that seen with tangential injection in PLT. The value of β_θ increases linearly with injected power up to 7 MW, even in low-current discharges where β_θ has reached 1.7 at high power.

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[1]Equipe TFR, in *Proceedings of the Eighth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium, 1980* (International Atomic Energy Agency, Vienna, 1981), Vol. II, p. 547.

[2]D. Meade *et al.*, in Ref. 1, Vol. I, p. 665.

[3]W. L. Gardner *et al.*, in *Proceedings of the Eighth Symposium on Engineering Problems of Fusion Research, San Francisco, 1979,* edited by C. K. McGregor and T. H. Batzer (IEEE, New York, 1979), p. 972; H. W. Kugel *et al.*, Princeton Plasma Physics Laboratory Report No. PPPL-1867, 1982 (unpublished).

[4]R. J. Goldston *et al.*, in *Heating in Toroidal Plasmas* (CEC, Brussels, 1981), Vol. II, p. 711.

[5]R. J. Hawryluk, in Proceedings of the Course on Physics of Plasmas Close to Thermonuclear Conditions, 1980, Report No. EUR FU BRU/XII/476/80 (unpublished), Vol. I, p. 19; R. J. Goldston *et al.*, J. Comput. Phys. 43, 61 (1981).

[6]F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys. 48, 239 (1976).

[7]W. Stodiek *et al.*, in Ref. 1, Vol. I, p. 9.

[8]V. S. Mukhovatov and V. D. Shafranov, Nucl. Fusion 11, 605 (1971).

[9]D. W. Swain *et al.*, Nucl. Fusion 21, 1409 (1981).

[10]P. J. Lomas *et al.*, in Proceedings of the Tenth European Conference on Controlled Fusion and Plasma Physics, Moscow, September 1981 (unpublished), Vol. I, paper A-1.